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White magnetic paper based on a bacterial cellulose nanocomposite

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ABSTRACT

A newly proposed idea for the fabrication of white magnetic paper is presented. These papers are fabricated from a layered composite of bacterial cellulose (BC) sheets. Magnetic BC sheets are prepared by the incorporation of CoFe_2O_4 nanoparticles (NPs) in the BC structure (MBC). White BC sheets were formed by the impregnation of ZnO NPs in the BC nanofibrils (ZBC), and then forming a ZBC/MBC/ZBC sandwich structure. This structure was then hot-pressed to obtain a white magnetic paper. The fabricated magnetic BC paper exhibits a ‘whiteness’ of over 80%, with a high reflectance of over 70% in the visible spectral range. XRD and SEM analysis confirmed the presence of the BC, CoFe_2O_4 and ZnO phases in the white magnetic paper. The whiteness of the paper is improved further with a higher concentration of ZnO NPs, but with the cost of a reduction in the mechanical properties. Magnetic hysteresis was observed for the fabricated white magnetic paper with a saturation magnetization of ~ 20 emu/g, comparable to the literature values for black magnetic papers. The white magnetic paper was demonstrated to exhibit flexibility and foldability just like regular paper sheets but can also be distinguished by subjecting to an external magnetic field. This gives potential for its use as security paper or for anti-counterfeit applications.

KEYWORDS: bacterial cellulose; nanoparticles; magnetic paper; ferrite; ZnO;

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Introduction

Cellulose is an almost inexhaustible raw material and a key source of sustainable materials on an industrial scale.¹ The use of fillers in a cellulosic paper network can deliver some unique functions which are not available in its pristine form.² In particular, magnetic cellulosic papers, in which magnetic particles are incorporated into the fibrous network structure, have attracted great attention from many research groups due to their potential uses for a wide range of technological applications, *e.g.* information storage, electromagnetic shielding, security paper, magnetographic printing, and magnetic filtering.³⁻⁸

Recently, several researchers have focused on magnetic papers or magnetic membranes based on a bacterial cellulose template. Bacterial cellulose (BC) is a form of the material with a microbial origin. It is commonly produced from the cultivation of a particular type of gram negative bacteria *e.g.* *Gluconacetobacter xylinum*. The material typically consists of a network of nanofibers with a large porosity. Bacterial cellulose has a number of advantages over plant celluloses, such as its high purity, high water absorbency, excellent biological affinity, and remarkable mechanical properties.⁹⁻¹¹ A number of studies on magnetic BC papers, films or membranes, synthesized by an *in situ* synthesis method, have been published.¹²⁻²⁰ For instance, Olsson *et al.* fabricated flexible magnetic aerogels and stiff magnetic nanopapers using BC nanofibrils as templates.²¹ They *in situ* synthesized CoFe₂O₄ nanoparticles (NPs) in the freeze-dried BC membranes, which exhibited both excellent mechanical and magnetic properties.²¹ In other research, flexible BC/permalloy nanocomposite xerogel sheets were fabricated by *in situ* co-precipitation of FeNi₃ NPs.²² Due to the metallic behavior of FeNi₃, the xerogel sheets showed both ferromagnetic and electrically conductive behavior. Lim *et al.* fabricated flexible magnetic papers by incorporating barium hexaferrite nanoplates in a BC matrix.⁷ The resultant product exhibited strong ferromagnetic properties and improved mechanical properties.

One obvious disadvantage of magnetic paper, when using either a plant cellulose base or a BC base, is the diminishing whiteness of the sheet. The magnetic papers in all of the above mentioned publications had dark colours.^{7-8, 12-22} White papers are commonly used in various applications²³⁻²⁴ but the introduction of magnetic particles typically destroys the whiteness, turning them black, or reddish-brown depending on the type of magnetic particles used. Non-magnetic papers, such as flexo and offset, also require a high degree of whiteness. Discolouration is

inevitable, since in ferromagnetic transition metals or oxides the Fermi level lies in the spin-splitting band; whiteness is typically found in a material with a large band gap. The diminished white colour appearance limits the uses of the magnetic papers. Another downside to the introduction of inorganic fillers in paper furnishes is the loss of strength of the sheet, something which is avoided in common printing paper (*e.g.* newsprint).

Some research has been reported on attempts to produce white magnetic paper, or improve the whiteness of magnetic paper. For instance, Gao *et al.* prepared magnetic paper by mixing Tb-based magnetic glass particles with hardwood chemical pulp by a lumen loading process.²⁵ The whiteness of the magnetic papers was found to be greater than 80%, even with the addition of more than 50 wt.% of magnetic particles. However, the papers in this work were paramagnetic, with very low magnetization (~ 0.1 emu/g), which cannot really be used in magnetic applications. Another example is the work carried out by Mo *et al.* who reported the addition of surface-modified graphene oxide (GO) coated magnetic particles incorporated into an oven-dried bamboo pulp.²⁶ The presence of GO improved the strength properties of the paper, but reduced the whiteness to below 70%, even for a small addition of GO (1.5 mg/mL). Again, paramagnetism was observed, since Tb-based magnetic glass particles were used in a similar approach to Gao *et al.*²⁵ Alternatively, Pacurariu *et al.* synthesized $\gamma\text{-Fe}_2\text{O}_3/\text{SiO}_2$ core shell NPs as possible candidates for magnetic paper pigments.²⁷ A SiO_2 shell coated on a $\gamma\text{-Fe}_2\text{O}_3$ core helped improve the whiteness of the particles, with the cost of a reduction in the saturation magnetization ($M_s = 0.8$ emu/g). However, only magnetic NPs were studied in this work, and magnetic papers were not fabricated. For magnetic paper based on BC, Zeng *et al.* have reported the synthesis of Fe_2O_3 NPs impregnated BC films by the aid of microwave-assisted thermal decomposition.²⁸ Ferromagnetism was observed in the synthesized papers, and the transparency was improved when a low concentration of NPs was used. The appearance of the paper was however far from white; the samples look reddish-brown or light-gold at best. Similarly, Barud *et al.* prepared flexible magnetic paper by the incorporation of well dispersed PEG- Fe_2O_3 in a BC matrix.⁶ A light brown colour was obtained, with a low Fe_2O_3 concentration, but darker shades were observed as more Fe_2O_3 NPs were introduced.

In the present work, we propose a new concept for the fabrication of white magnetic paper based on BC templates; by using a composite approach to their production. A magnetic BC

network is sandwiched between two white BC network layers, comprised of BC plus ZnO NPs. Using this simple approach, ferromagnetic papers with the preservation of whiteness, can be fabricated. As far as we are aware, this is a novel approach and has not been previously reported.

Experimental

Materials

The chemicals used for fabricating magnetic BC papers were iron (III) chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, Reagent grade, Sigma-Aldrich), cobalt (II) chloride hexahydrate ($\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, Reagent grade, Ajax Finechem), Zn (II) chloride (ZnCl_2 , Reagent grade, Rankem), sodium hydroxide (NaOH, 99%, RCI Labscan), Yeast Extract Powder (Himedia) and D-Glucose (anhydrous AR, Ajax Finechem).

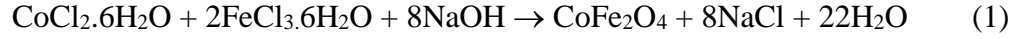
Production of BC Membranes

BC membranes were produced by cultivating the bacteria *Gluconacetobacter xylinum* (strain TISTR 975), supplied from the Microbiological Resources Center, Thailand Institute of Scientific and Technological Research (TISTR). The medium used in the bacteria culture consisted of 100 g of D-Glucose and 10 g of yeast extract in 1 L of de-ionized (DI) water (GYE medium). After incubating in an incubator (Termaks, KBP-6395F) for 3 days under static conditions at 30 °C, BC pellicles with a thickness around 0.3 cm were harvested and purified in boiling DI water. They were then soaked in 0.5 M and 5 wt% NaOH for 15 min and 24 h respectively. To ensure that no contamination occurred, the BC pellicles were rinsed further with DI water several times until a pH of 7 was reached. Finally, BC hydrogels obtained from this step were either kept under this condition (never-dried state) or in a freeze-dried (FD) state for the synthesis of nanocomposites in the next step.

Preparation of BC Nanocomposites

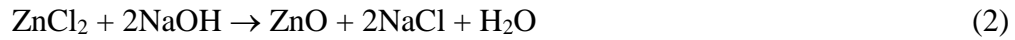
Two nanocomposites were fabricated; namely BC + magnetic NPs, and BC + ZnO NPs. The former is labelled as MBC and the latter as ZBC. To synthesize MBC, co-precipitation between $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ in the presence of the FD-BC template was carried out using

NaOH as a reducing agent. Firstly, 0.05M of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ and 0.10M of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were dissolved in 50 ml of DI water. The FD-BC was soaked in the prepared solution which was then heated to 60 °C and held for 4 h. After that, 100 ml of 1.2M NaOH was added to convert the metallic ions into cobalt ferrite (CoFe_2O_4) NPs according to the chemical reaction:



The products were rinsed with water several times to remove unwanted materials until a pH of 7 was reached. The MBC in the form of a hydrogel was obtained.

For the synthesis of ZBC, ZnCl_2 was dissolved in 50 ml of DI water. The never-dried BC pellicles were then immersed in the zinc chloride solution for 24 h before soaking in NaOH solution at 55 °C for 1 h with continuous stirring. The BC + ZnO nanocomposites were formed according to the chemical reaction:



The effect of ZnCl_2 concentration on the whiteness of the samples was also explored. Two ZnCl_2 concentrations were used, 0.05M and 0.10M, for this purpose. The nanocomposite samples from these two concentrations were labeled as ZBC(1) and ZBC(2). The final products were then rinsed with water several times to obtain the ZBC hydrogels.

Fabrication of Magnetic Papers

Magnetic papers in this work were fabricated by hot-pressing BC hydrogels in an oven at 80 °C for 24 h. Four types of papers were prepared: BC/BC paper, MBC paper, BC/MBC/BC composite paper, and a ZBC/MBC/ZBC composite paper. For BC/BC and MBC papers, double layers of BC or a one-layer MBC sheet was compressed. In the case of BC/MBC/BC or ZBC/MBC/ZBC composite papers, an MBC sheet was sandwiched between BC or ZBC sheets before hot-pressing (0.2 MPa at 80 °C). The final thickness was approximately 0.03 mm per sheet. The fabrication process for these materials is summarized in Fig. 1.

Characterization of the Samples

The whiteness of the papers was measured at the Department of Science Service, Ministry of Science and Technology, Thailand, according to the ISO 11476:2010 standard. A UV-visible spectrometer (Shimadzu, UV-3101PC) was used to collect the optical absorption spectra in the wavelength range 200 – 800 nm. X-ray diffraction (XRD) was carried out using a diffractometer employing Cu-K α radiation (PANalytical, Empyrean) in a 2θ range of 5 - 80° to collect the information on the NPs' phases and crystalline structures. A field emission scanning electron microscope (FESEM) (FEI, Helios) was used to observe the surface morphologies and cross-sectional images of the samples. Prior to imaging with the SEM, the samples were gold coated to improve conductivity. For the mechanical properties tests, the tensile strength was measured using a universal testing machine (UTM, Instron 5567A) with a 20 mm sample gauge length, a sample width of 15 mm and a 20 mm/min testing speed. All tensile testing was conducted at 25 °C and 55% humidity. Tensile index was calculated according to the TAPPI T 494 standard. The tear index was tested at the Department of Science Service, Ministry of Science and Technology, Thailand, according to the ISO 1974:2014. Magnetic properties were investigated by measuring magnetization (M) versus magnetic field (H) using a vibrating sample magnetometer (VSM) option in the VersaLab instrument (Quantum Design, USA) under a maximum field of 20 kOe.

Results and discussion

Fig. 2 shows photographic images, without any colour adjustment, of the fabricated BC paper samples. The BC/BC paper shows a faint white colour with some degree of opacity. As expected, the introduction of magnetic NPs turned the MBC sample black, on account of the black colour of the CoFe₂O₄ powder. For the BC/MBC/BC composite, since the MBC was covered with a layer of a transparent BC, the dark colour of the interior layer can still be visible. Thus, the composite looks light gray, on account of the combined colour of both MBC and BC. Although the colour appearance of the BC/MBC/BC composite has improved significantly (much whiter than MBC), it is still far from the shade of a normal white paper. Finally, the ZBC/MBC/ZBC sample exhibits a much whiter colour, due to the whiteness of ZnO NPs. This sample looks similar to normal white paper.

To quantify the level of whiteness, a test according to the ISO 11476:2010 standard was performed, the results of which are presented in Fig. 3a. The whiteness of the BC/BC paper is relatively low ($\sim 32\%$), and introducing the magnetic NPs resulted in a decreased whiteness ($\sim 27\%$) for the MBC paper. On the other hand, the ZBC/MBC/ZBC composite papers exhibit a whiteness of greater than 75%. In particular, for a higher concentration of ZnO, the ZBC/MBC/ZBC(2) exhibits a whiteness of nearly 85%. This suggests that using a more concentrated ZnO content can improve the whiteness of the paper. This increase in whiteness however comes at the cost of a reduction in the magnetization, and inferior mechanical properties. Compared to other published work, the whiteness of our magnetic paper is higher than literature values for magnetic papers where Tb-based magnetic glass NPs were employed.²⁵⁻²⁶ The UV-visible spectra in Fig. 3b also confirms the photographic images and whiteness tests. Within the visible spectral range (400 – 700 nm), the reflectance of the BC/BC paper is approximately 30 – 35% corresponding to an opaque white appearance, as seen in Fig. 2. The addition of CoFe_2O_4 significantly suppressed the reflectance in the visible (and UV) ranges, resulting in a black appearance to the MBC paper. This is due to the very low reflectance of CoFe_2O_4 NPs in the visible range, as has been previously reported.²⁹ However, incorporation of ZnO NPs in the ZBC/MBC/ZBC nanocomposites result in a substantial increase in the reflectance in the visible range, but a reduced reflectance in the UV range compared to the pristine BC paper. This is to be expected, since the ZnO nanostructures have been reported to exhibit very high reflectance in the visible range.³⁰⁻³¹ The observed high light absorption in the UV region (at wavelengths below 356 nm) is probably due to the ZnO band gap, which is a common characteristics of these NPs.³² It is also known that the size of ZnO particles has an effect on the light UV absorption properties, this being one of the principles behind sunscreens. As previously reported, the UV absorbance of ZnO NPs (in the size range above the quantum limit) increases with increasing particle sizes.³³ Increasing the concentration of ZnO (ZBC/MBC/ZBC(2)) led to the higher reflectance in the visible region, compared to ZBC/MBC/ZBC(1), corresponding to an increase in whiteness as shown in Fig. 3a. These results verify our proposed concept idea showing that we can successfully produce white magnetic paper based on BC nanocomposites.

To obtain information on the phase formation in the BC papers, XRD patterns were collected, the results of which are shown in Fig. 4 along with reference patterns for ZnO and CoFe_2O_4 . For the pristine BC paper, only three diffraction peaks corresponding to $(1\bar{1}0)$, (110)

and (200) reflections of the BC crystalline structure were observed.³⁴ In the MBC sample, the combined XRD peaks from both BC and CoFe₂O₄ crystalline phases were observed, indicating a successful incorporation of cobalt ferrite NPs in the BC network structure. The reduction in the peak intensities from the BC was possibly caused by the intense reflection from the CoFe₂O₄ NPs, and even the deterioration of the BC's crystallinity as the CoFe₂O₄ NPs were introduced. These observations have been previously reported.^{8, 13-14, 16, 18-19} For the composite papers, the BC/MBC/BC sample again shows the presence of both BC and CoFe₂O₄ phases, but the peaks for the BC phase are more intense than for the cobalt ferrite phase. The reason for this increase in intensity could be that it is a sandwich structure, and so there is a larger scattering volume from the top BC layer, resulting in more intense reflections from this material. The scattering volume of the CoFe₂O₄ phase is comparatively low compared to the BC layers, and so reduced intensity XRD peaks are observed for this material. For the white ZBC/MBC/ZBC paper, the mixed crystalline phases of BC, CoFe₂O₄, and ZnO can all be identified. Strong reflections from the BC as well as those from ZnO were observed; this indicates that the structure of the BC was not significantly affected by the incorporation of ZnO NPs. This is a similar result to that obtained for BC-ZnO nanocomposites.³⁵⁻³⁶

Typical SEM micrographs of the plan-view images of the BC paper and MBC paper are shown in Fig. 5a and 5b, respectively. In order to image the inner structure of the fibrillar network, the top surface was peeled off before SEM imaging. The BC paper consists of numerous nanofibers woven randomly in the plane. The diameter of each fibril is of the order of ~100 nm. On the other hand, the SEM image of the MBC paper showed that CoFe₂O₄ NPs were coated on the surface of the BC nanofibrils. The NPs were distributed evenly all over the BC structure, indicating a homogeneous synthesis of the cobalt ferrite NPs in the BC network template. Unlike FD samples, where a porous structure is preserved,^{8, 15, 21} the porous structure is found to have collapsed due to the hot-pressing process to form the paper sheet. This resulted in very dense samples with few pores in the nanometer range. Fig. 5c shows an image of the cross-section of the BC/MBC/BC composite paper. The thickness of each layer is ~20 μm. The composite sheets are not well attached to one another, and clear interfaces are visible between the layers. On the other hand, the cross-sectional image of the ZBC/MBC/ZBC paper (Fig. 5d) shows that the nanocomposite BC sheets are seamlessly joined, probably due to fibril-fibril bonding induced in the dried state. The difference between the cracked interfaces of the BC/MBC/BC paper and the seamless interfaces

of ZBC/MBC/ZBC paper can possibly be explained as follows. It is well known that BC has a large number of labile -OH groups on its surface,¹⁰ making it negatively charged. During the *in situ* synthesis process, either CoFe_2O_4 or ZnO NPs are thought to anchor to these -OH sites leading to the neutralization the BC nanocomposite. The BC/MBC interface thus consists of one negatively charged BC sheet and another neutral MBC sheet, and hence cannot bond very well. On the other hand, the ZBC/MBC interface can be bonded better due to no charge difference.

The mechanical properties of the BC papers are shown in Fig. 6. It is clear that both the tensile index and tearing index (Fig. 6a) of the BC/BC sample is the highest amongst the sample set. It is also very ductile and highly flexible (strain $> 20\%$, *cf.* Fig. 6b). This is due to the excellent mechanical properties of the pure BC membrane.^{1, 37} Fig. 6b shows the typical stress-strain curves of the BC-based papers. All curves exhibit typical non-linear stress-strain behavior. The MBC sample exhibited the lowest tensile and tearing indices. Incorporation of magnetic NPs in the BC structure generally deteriorate the BC network strength,^{7-8, 14, 19} partly due to the modification of the BC functional groups,⁸ but also due to the interruption of the inter-fibrillar bonding.¹⁴ Furthermore, the MBC becomes very brittle with a very limited flexibility (strain $< 2\%$, *cf.* Fig. 6b). The mechanical properties of the sandwich-structure paper, BC/MBC/BC were much enhanced compared to the MBC sample. This is understandable since in the sandwich structure, there are two sheets of pure BC which help to retain flexibility. Introducing ZnO in the BC structure (ZBC/MBC/ZBC(1)) results in a decrease in the mechanical properties. Again, it is thought that the presence of ZnO NPs causes a reduction in inter-fibrillar bonding.^{8, 14} Using higher concentrations of ZnO NPs (ZBC/MBC/ZBC(2)) leads to a further drop in mechanical properties. As mentioned previously, impregnation of ZnO improved the whiteness of the magnetic paper; the more concentrated ZnO , the whiter the paper becomes, but with the cost of a reduction in mechanical properties.

Measurements of the magnetic properties of the BC based papers are presented in Fig. 7a. As expected, pristine BC does not exhibit ferromagnetic behavior. For other samples, magnetic hysteresis loops are observed. The inset to Fig 7a shows the difference in the height and width of the loops. Therefore, we extracted the saturation magnetization (M_s) the magnetic remanence (M_r) and the coercivity (H_c) from the hysteresis loops, which are presented in Fig. 7b. The largest values of M_s , M_r and H_c belong to the MBC paper due to the highest portion of the magnetic NPs in these samples. These values are reduced in the BC/MBC/BC and ZBC/MBC/ZBC samples since the

weight fraction of the magnetic cobalt ferrite was diluted with non-magnetic phases (BC and ZnO). Interestingly, the white magnetic paper (ZBC/MBC/ZBC(1)) in the present study shows a relatively large M_s value of ~ 20 emu/g, comparable, if not higher than some literature values for the black magnetic BC membranes ($\sim 8 - 26$ emu/g).^{7, 12, 17-18, 22} This shows that this sample has very favourable magnetic properties, and can be highly sensitive to an external magnetic field which could be exploited in several potential applications.

To demonstrate the magnetic responsive behavior of the white magnetic paper, the ZBC/MBC/ZBC(1) sample was tested with a permanent magnet. As shown in Fig. 8, it is easily bent towards or can be lifted by a magnet. The magnetic paper in our work is highly responsive to an external magnetic field similar to other reports^{6, 12, 14, 18-19, 21-22} but most distinctly and importantly it retains its white appearance. Moreover, Fig. 9 illustrates the flexibility and foldability of the white magnetic paper. Fig. 9a shows that the fabricated paper in this work can be rolled just like normal paper. It can be also folded into an origami swan starting from the 3-cm-square sheet (Fig. 9b). As demonstrated in Fig. 9c and 9d, the origami swans made from our white magnetic paper are visually indistinguishable from the swans made from normal white paper, but can be identified by their magnetic properties. This experiment suggests a variety of applications for such white magnetic paper, for example, security paper or anti-counterfeit applications.

Finally, a printing test was demonstrated using the fabricated white magnetic paper in this work as a substrate. As shown in Fig. 10, the image printed on the ZBC/MBC/ZBC(1) paper was almost indistinguishable from the same image printed on a standard A4 80 gsm paper. The printed white magnetic paper is however magnetic. This demonstrates the printability of the white magnetic papers in this work, while also maintaining their magnetic properties. These properties make them comparable to a one-side white magnetic paper commercially available in the market (for example, the Quirkii® product). However, the commercial one-sided white magnetic paper is based on a bound system (embedded magnetic particles in a rubber sheet) adhesively attached on a paper sheet. Although it is very useful for printing or sticking notes on metallic surfaces, or for education, it is visually different to normal A4 paper. Our white magnetic paper, on the other hand, looks very similar to normal white paper, so that it can be used in many different applications. Moreover, the price of the commercial product is relatively high ($\sim \$4.8$ per 1 A4 sheet). The cost

for the fabricated sample in the present research is estimated to be less than \$3 per A4 sheet, and this cost could be much lower for production on an industrial scale.

Conclusions

White magnetic paper, based on a composite sandwich structure comprising a ZBC/MBC/ZBC sheet, has been fabricated using a nanocomposite approach and by hot-pressing. A white colour appearance was observed for these materials, just like a normal paper, with a whiteness of 75-85% corresponding to high reflectance in the visible range. The XRD analysis showed the formation of the ZnO and CoFe₂O₄ phases in the BC nanofibrillar network structure. The SEM micrographs showed that there was a homogeneous distribution of CoFe₂O₄ NPs coated on the BC nanofibers' surfaces, and the seamless interfaces between ZBC and MBC layers. The mechanical properties were significantly reduced for the MBC single sheet but enhanced for the ZBC/MBC/ZBC composite papers. The white magnetic paper also exhibited flexibility, rollability and foldability, just like a normal paper. Magnetic measurements showed a ferromagnetic property with a relatively large value of M_s (~20 emu/g). This value corresponded well with the magnetic responsive behavior of the fabricated paper to an external magnetic field. The combined characteristics of the white appearance, magnetic sensitivity and good mechanical properties make our newly proposed white magnetic paper potentially useful for a wide range of applications.

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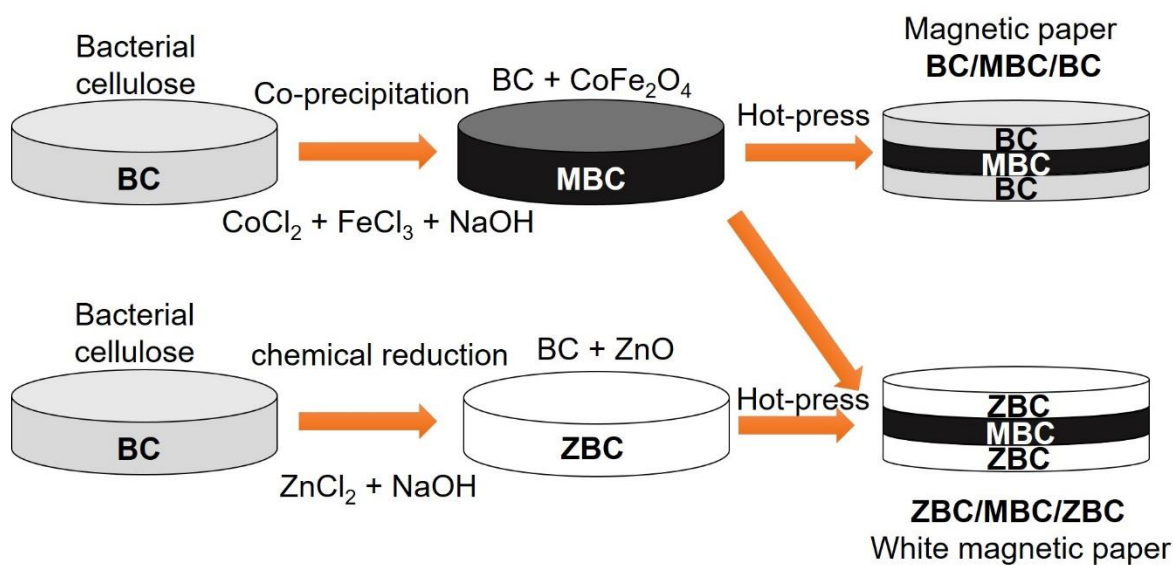


Fig. 1. Schematic of the synthesis process for white magnetic paper based on magnetic BC nanocomposites.

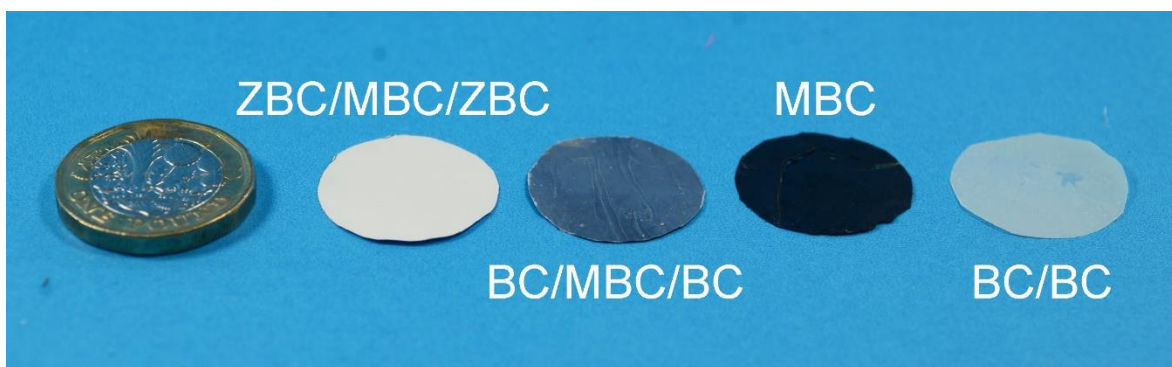


Fig. 2. Images of the synthesized samples. A one-pound coin is used as a scale bar (far left) and a colour indicator. This figure is shown without any colour adjustment.

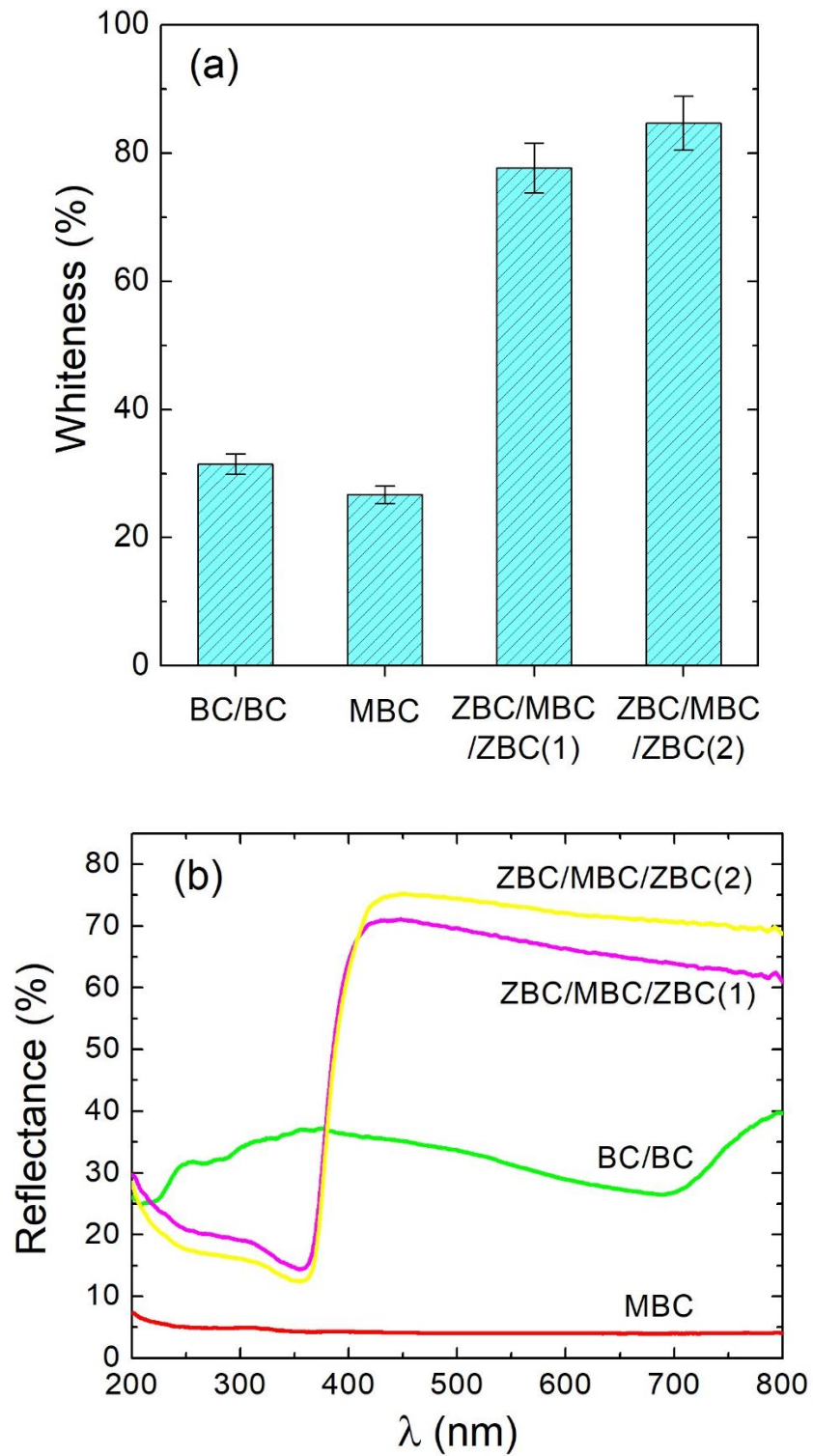


Fig. 3. Measurements of (a) the whiteness and (b) the UV-vis reflectance for the BC based papers.

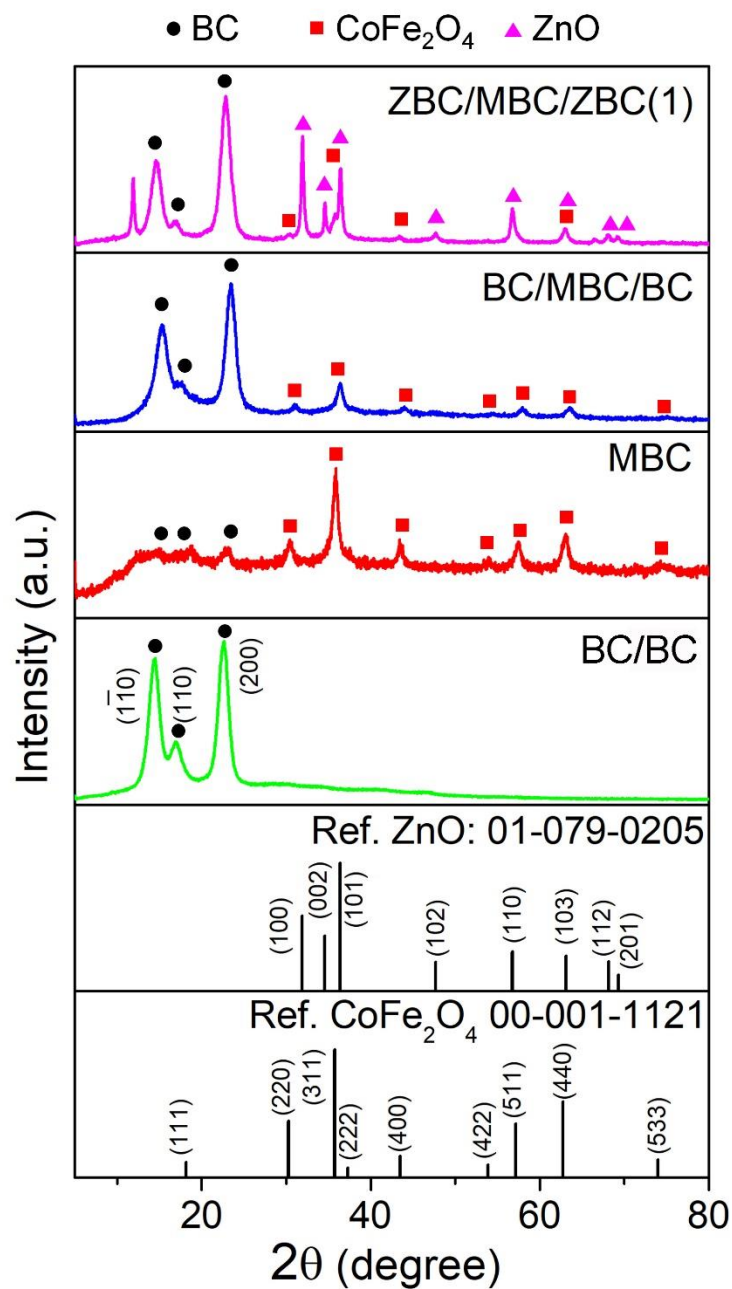


Fig. 4. Typical XRD patterns for the synthesized samples showing the mixed phases in the nanocomposite samples.

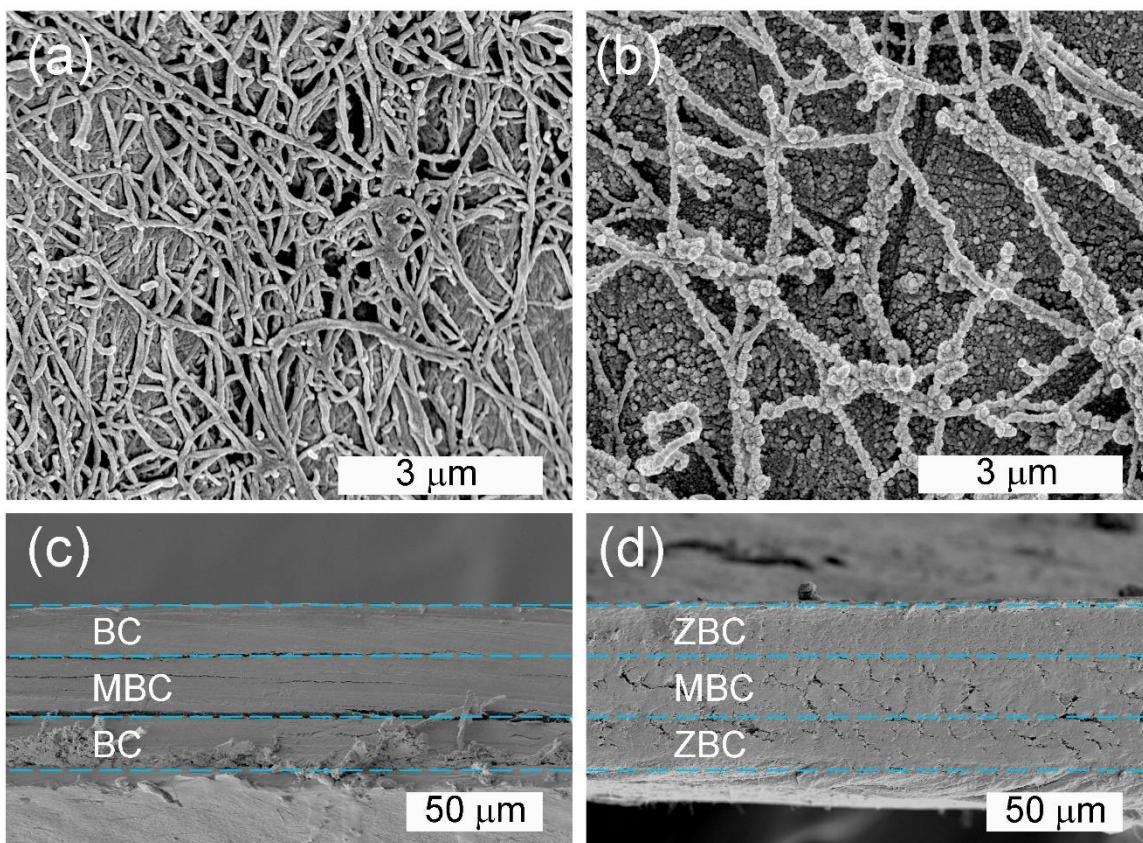


Fig. 5. Typical SEM images of the plan-view (a) BC/BC and (b) MBC samples, and cross-sections (c) BC/MBC/BC and (d) ZBC/MBC/ZBC.

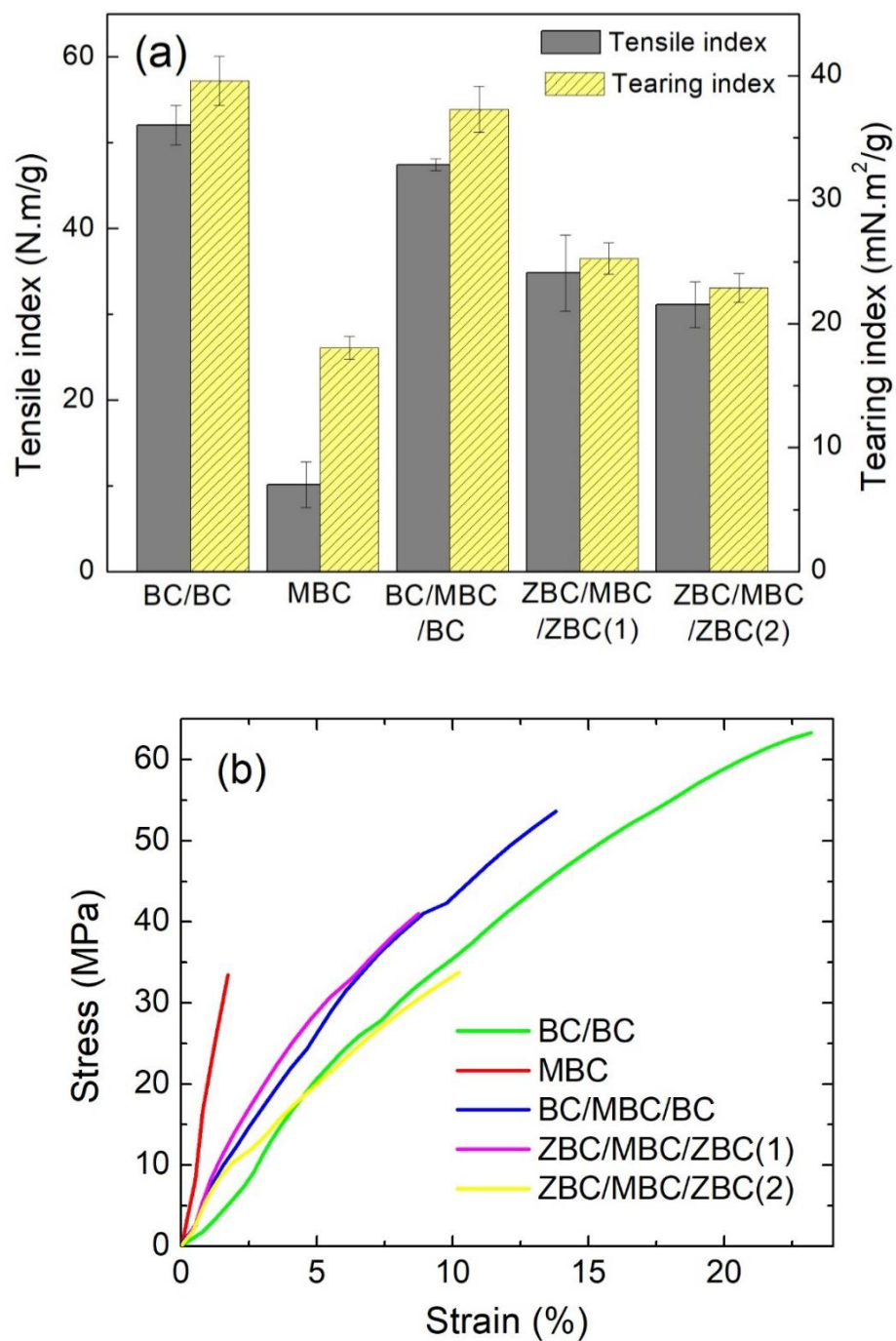


Fig. 6. (a) Tensile index and tearing indices of the magnetic BC papers; (b) Typical stress-strain curves for the samples.

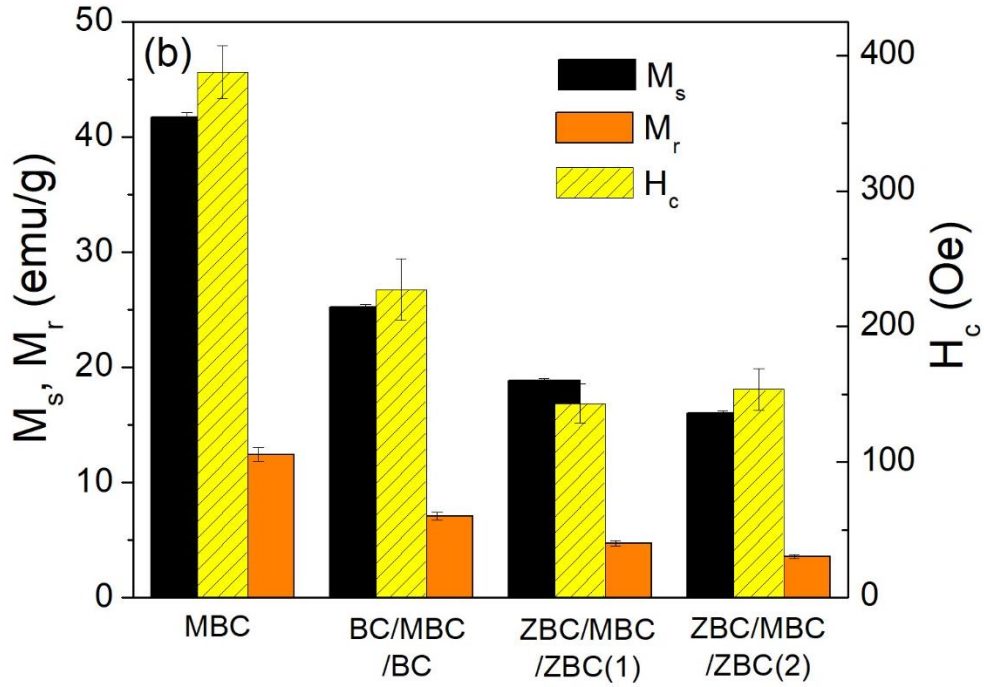
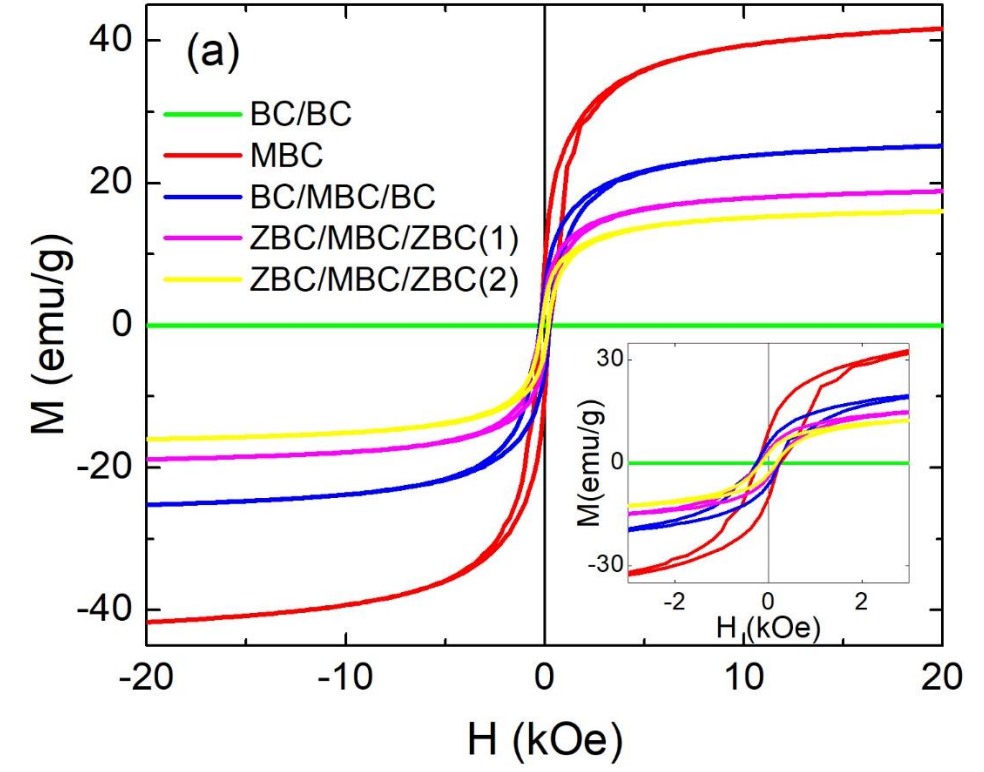


Fig. 7. (a) M-H curves of the synthesized samples, with a magnified view in the inset; (b) M_s , M_r and H_c parameters extracted from the M-H curves.

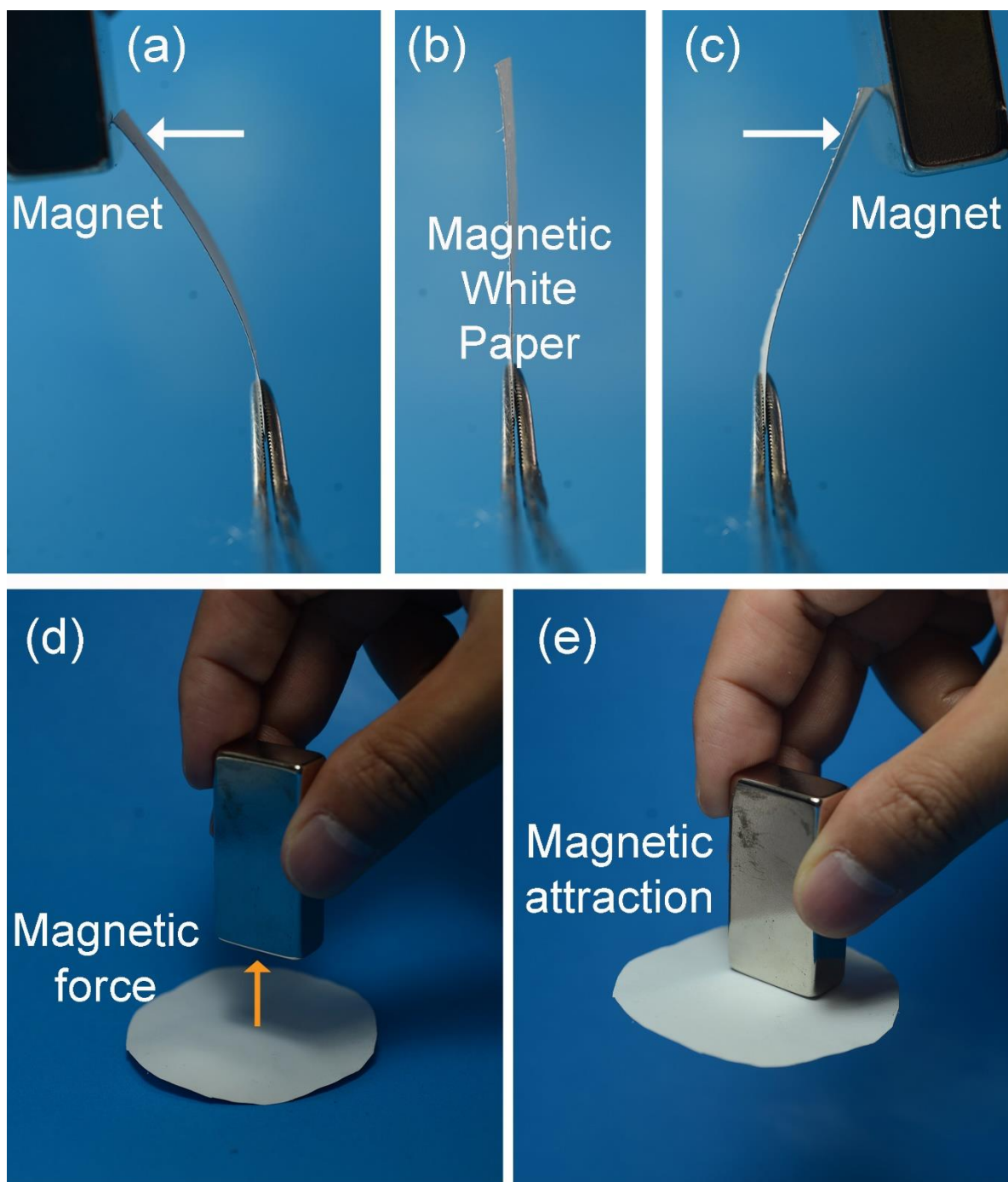


Fig. 8. Magnetic response of the white magnetic paper (ZBC/MBC/ZBC) to a permanent magnet: (a-c) bending towards the magnet, (d-e) magnetic lifting.

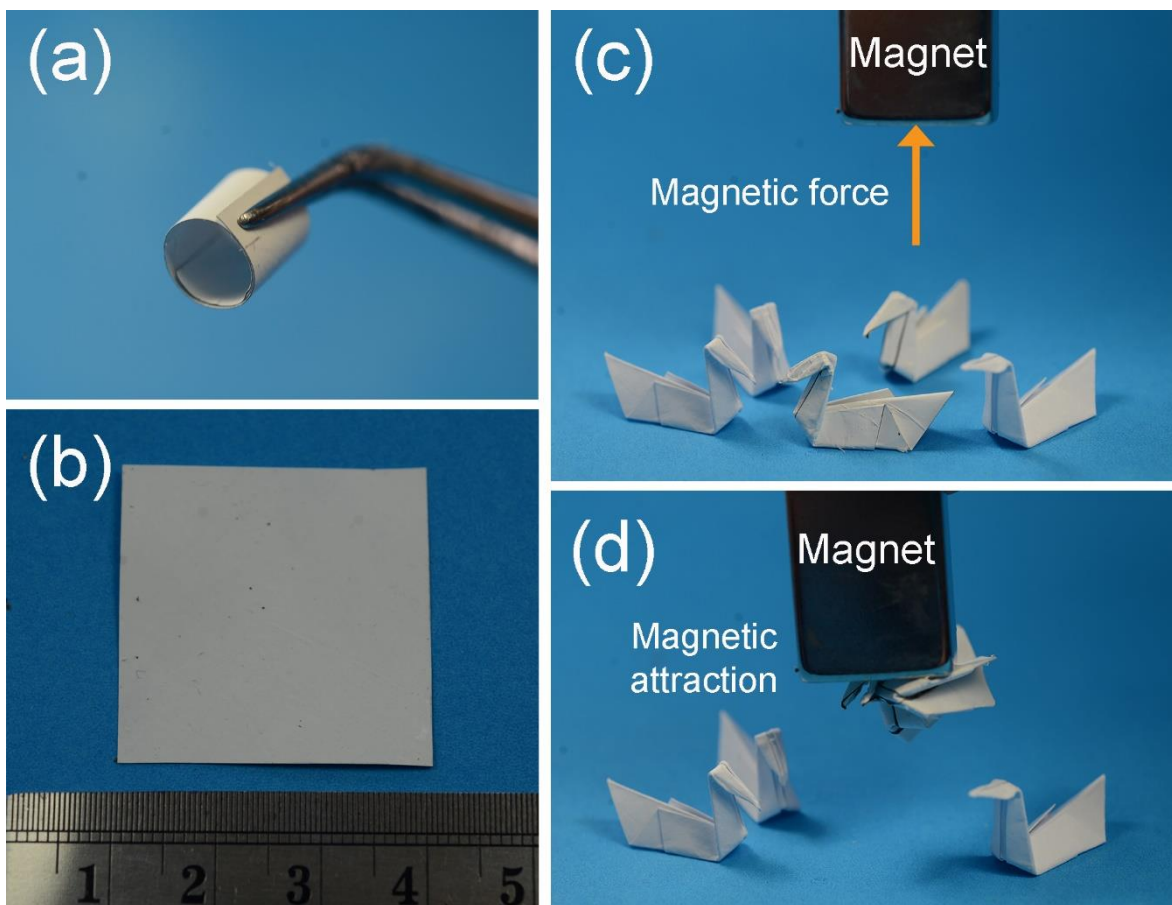


Fig. 9. (a) Demonstration of the flexibility of the white magnetic paper, (b-d) foldability of the paper to form the white swan origami. The swan made from the BC magnetic paper looks just like those made from normal papers but can be separated by a magnet.



Fig. 10. (Upper) Demonstration of the printability of the white magnetic paper (right), compared to the same image printed on a standard A4 80 gsm paper (left). (Lower) The printed white magnetic paper can be lifted by a magnet.